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THE METEOROLOGY OF TOMORROW

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THE METEOROLOGY OF TOMORROW

P. Morel

ABSTRACT. A resume of where we have been, where we are, and where we will be in the future in the field of meteorology by a distinguished professor at the University of Paris-VI, and the Deputy Director of the Laboratoire de Météorologie Dynamique of the CNRS, the National Scientific Research Center.

Meteorology, long considered a minor field by the scientific community, has /345* not enjoyed the favor of a sceptical public, but it is in the process of changing its image for the future, thanks to satellites and to large computers capable of processing the information fed into them. According to all those present at the VIth Assembly of the International Union of Geodesy and Geophysics in Moscow last August, the study of the dynamics of the atmosphere should very soon be the center of attraction in geophysics, particularly when such major international programs as the Veille Météorologique Mondiale [Worldwide Meteorological Watch] and the Global Atmospheric Research Program, set for the near future, get underway.

Why this infatuation? The advent of space techniques, offering as they do an exceptional experimental tool, certainly is the main reason. And one can also add to this definite economic motives, for, as Pierre Morel says in his article, "weather forecasting no longer is a free art, nor is it a purely scientific undertaking. It is a factor that often is essential in planning our activities, a service necessary to a more productive economy."

Looking at the atmosphere of our planet from the point of view of astronomy, /346 the conclusion is inescapable that we are blessed with a particularly mild and untroubled environment, one in which the whims of the weather are minor as compared to changes that are conceivable, and take place, in other places. The earth's relatively strong magnetic field blocks out most of the ionizing particles and teratogenesis that otherwise would inundate the planet. The ozone layer in the stratosphere absorbs ultraviolet radiation from the sun which otherwise would sterilize all life on the surface. The oceans play the part of huge heat

* Numbers in the margin indicate pagination in the foreign text.

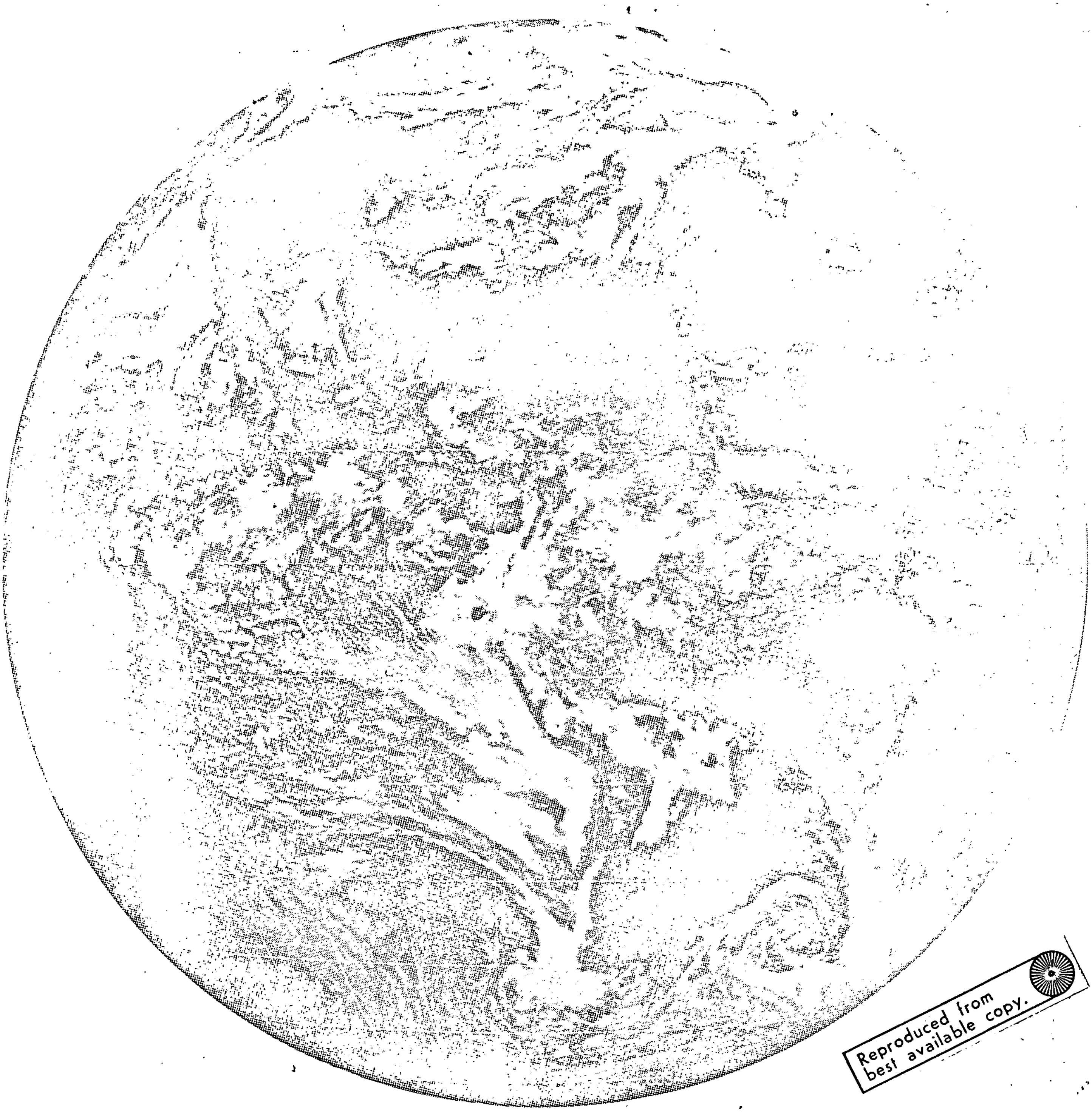

Figure 1. A photograph of the cloud cover over one-fourth of the earth's surface, taken on 23 June 1971, at 1532 UT by the ATS-3 satellite. The geographic grid obviously was added after the photograph was taken. (NASA negative).

reservoirs for regulating the air temperature everywhere except in regions deep within continents, and the desert regions. In a word, then, it is reasonable to think that our planet offers to its inhabitants a climate that is particularly benign, and if, now and then, some meteorological catastrophe "makes the front page" of the news, it is simply because it is so rare. All things considered, even the torrential rains had only to flood the Euphrates and Tigris valleys, and the history of Noah shows that he could escape without any great nautical skill!

Considering that weather phenomena are, after all, quite bearable (particularly in the temperate zones where we happen to live), and that they are, at least for the time being, quite beyond our intervention, why all the effort to forecast, with more or less pleasure, what the weather will be tomorrow? Our forefathers took a more fatalistic attitude toward this subject and did not do badly. When the weather hampered their activities they waited until the storm blew itself out, or until the cold weather was over, and that was all there was to it.

This wisdom, quite oriental, still is, as a matter of necessity, the attitude of the majority of the earth's population. But it no longer is possible for us, because the economic development path upon which we are embarked requires an efficiency, a rising productivity, that is incompatible for the future with all forms of fatalism concerning our environment. The economic margins we operate on are too narrow for us to authorize standing by, inactive, until the rain, or the drought, is over to enable us to risk planting some particular type of grain and hope that nature will be benevolent. Quite the contrary, it has become indispensable that we plan our work and our choices to attain this material abundance to which, consciously or not, we look forward to so much. That is why weather forecasting no longer is a free art, nor is it a purely scientific undertaking. It is a factor that often is essential in planning our activities, a service necessary to a more productive economy.

Moreover, the pressure we exert on the natural environment in our use of it for production, as well as for leisure, is such that we cannot reasonably hold to the unconcerned attitude of our forefathers that nature is boundless. We have to weigh the consequences of our industry, and of our choices in that domain. This is why the ecology and the physics of the atmospheric phenomena that govern the climate no longer are free arts, nor purely scientific undertakings, but rather are necessary knowledge, at least for our well-being, and perhaps even for our survival.

"The plot thickens," as the humorist puts it. And the plot has indeed thickened in this increasingly complex and increasingly performing system of communications we call modern society. Like telecommunications, automatic data processing, and the development of individual modes of transportation, forecasting and meteorological science will be another facet of the complicated world of tomorrow, and not a simple one, as we shall show.

The Atmosphere: A Heat Engine

The stable state for a homogeneous fluid placed in a cylindrical container turning uniformly about its axis, water in a bucket, for example, is an identical rotation such that the fluid and container act like a solid block. In this case there is no differential movement within the fluid, of course, nor is there any relative movement of the fluid with respect to the container. The solid planet is such a container, and it is the planet, not the atmosphere, that rotates. The atmosphere would follow planetary rotation precisely if there were no heterogeneity or variation in air density, and there would be no wind.

This static atmosphere can contain a great amount of internal energy, an amount corresponding to the heat it has absorbed, as well as a great amount of potential energy in the earth's gravity field, but no kinetic energy, in a local datum tied to the planet. Nor would there be a gradient to transform potential energy into motion in this uniform atmosphere. One can say that potential energy is not available.

One could calculate the equilibrium temperature for a model of a static atmosphere by listing the radiation exchanges between the air and the ground (the hot source) and between the air and space (the cold source). Briefly, then, one can say that a significant part of the solar radiation passes through the atmosphere and reaches the ground, where it is absorbed (about 50%, with the balance being reflected, or diffused toward space). This radiation flux produces a heating effect, which, in turn, warms the lower strata at the same time that the atmosphere overall, and curiously, the upper strata, is cooling while emitting strong infrared radiation in the 10 to 30 microns band towards space. This /347
process would create a temperature gradient that would become steeper between the

surface and the high atmosphere were it not limited by convection, a well-known form of instability of a stratified fluid. The warm air rises, the cold air descends, producing a mixture that fixes the temperature gradient at what is very nearly a constant value; 6.5° per kilometer of altitude. These vertical movements are quite comparable to the "drawing" of a chimney, or to the outflow of hot and cold air around a heater. They are relatively rare in the temperate zones, but are quite frequent in the tropics, where they manifest themselves by the formation of heavy clouds which, like chimneys, pierce the atmosphere from the base to the summit.

As important as these phenomena are in explaining the sources of energy that stir up the atmosphere, we shall consider but one very simple one among them, and that is that the equatorial atmosphere is hotter than the polar atmosphere because the former, on the average, receives more solar radiation. Thus, the terrestrial atmosphere is not a homogeneous fluid system. While the pressure is about equal, polar air is denser than tropical air, and centrifugal force tends to create a circulation moving the denser air towards the equator while moving the lighter air toward the axis of rotation (Figure 2).

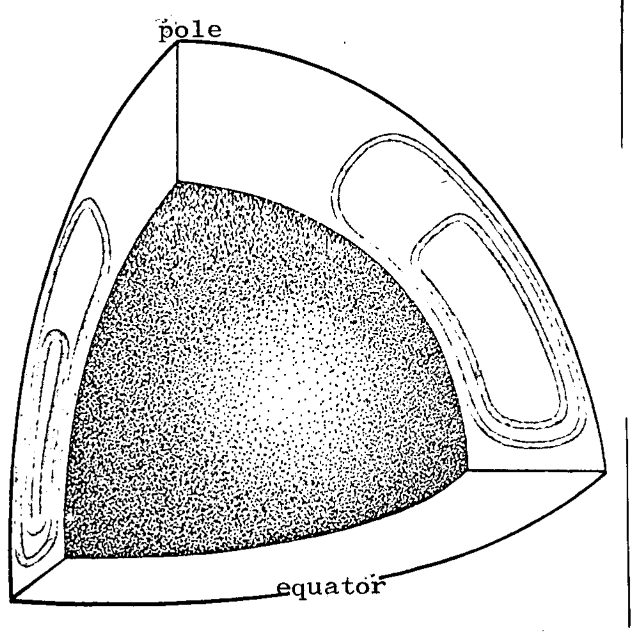

Figure 2. Meridional circulation of the air for a rotating planet, caused by the contrast in the equator-pole temperature. The polar air is denser than the tropical air. Centrifugal force tends to create a circulation that will move the denser air toward the equator and the lighter air toward the poles. This circulation stops near 30° north and south latitudes on the earth (Hadley cell). The depth of the atmosphere is greatly exaggerated.

This meridional circulation, which successively puts the air compressed by atmospheric pressure in contact with the planet's warmer zones, and that expanded at high altitude in contact (radiative) with the cold of space, is a thermodynamic cycle exactly like that of a heat engine. This cycle of transformation evidently is the source that maintains the mechanical energy of the atmosphere and produces the winds. Perhaps it is useful to emphasize that this system, in the reality of geophysics, has an extremely low efficiency, because the potential energy <u>available</u> at any given moment is but 1% of the total potential energy, and the kinetic energy of the winds is but 1 °/oo of this quantity. This shows just how little disturbance meteorological phenomena make in the static state, and, as a result they are difficult to calculate with precision.

<u>Atmospheric Circulation Is a Turbulent Flow</u>

Elementary mechanics shows at once that the meridional circulation depicted in Figure 2, while itself very slow, can be accompanied by a rapid zonal circulation. This is the result of the conservation of the moment of momentum of the air with respect to the planet's axis of rotation. A bit of air accompanying the rotation of the earth at the equator is accelerated to an absolute speed /348
of 1,666 km/h. As it moves toward the pole the distance to the axis of rotation diminishes, and the speed should increase in proportion. Lacking any braking applied to the other parts of the atmosphere, the absolute speed of the bit of air would reach 2,360 km/h at a latitude of 45°, or twice the speed of the sun at this locality. The relative wind would, at the same time, reach the fantastic speed of 1,180 km/h!

Our planet has no such atmospheric currents, although one does find "jet streams" of 200 km/h at the altitudes at which modern aircraft fly, and winds of 400 km/h in the high stratosphere. But we know that these swift jets surpass the acceptable limit of speed for a laminar, steady-state, and regular system. Flows such as these are unstable and quickly generate oscillations and meanders of all sorts, as is a frequent occurrence in fluid mechanics. An example is a laminar and steady-state stream of water obtained by making the necessary adjustment to the flow from a faucet. The stream becomes unstable and begins to break up when the adjustment is increased above some limit. The situation is the same for the circulation of the planetary atmosphere. The wind reaches the limit set by the geometry and the dynamic characteristics of the flow at some distance from the equator, and the regular, constant circulation characterizing the tropical zone breaks up to become a disturbed flow in which the meanders change constantly (Figure 3). These huge disturbances, the amplitudes of which are in the thousands of kilometers, are clearly visible on the maps compiled daily by the weather services (Figure 4). Not visible, however, are the countless shorter, briefer oscillations that form a hierarchy of movements on a decreasing scale, without discontinuity. The flow of the atmosphere is a very complex movement, the components of which range from the great waves on a planetary scale to the briefest gusts of atmospheric turbulence. All these movements appear to be disorganized with respect to each other and interact with each other like ocean waves.

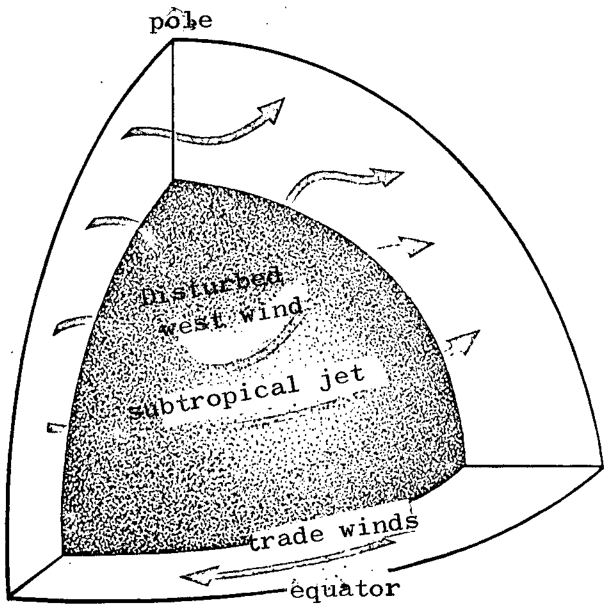

Figure 3. General circulation of the atmosphere. Note the east (trade) winds at the equator and the west winds, at increasing speed, at the higher latitudes. The undulating disturbances are caused by instability in what is purely zonal flow above 30° latitude.

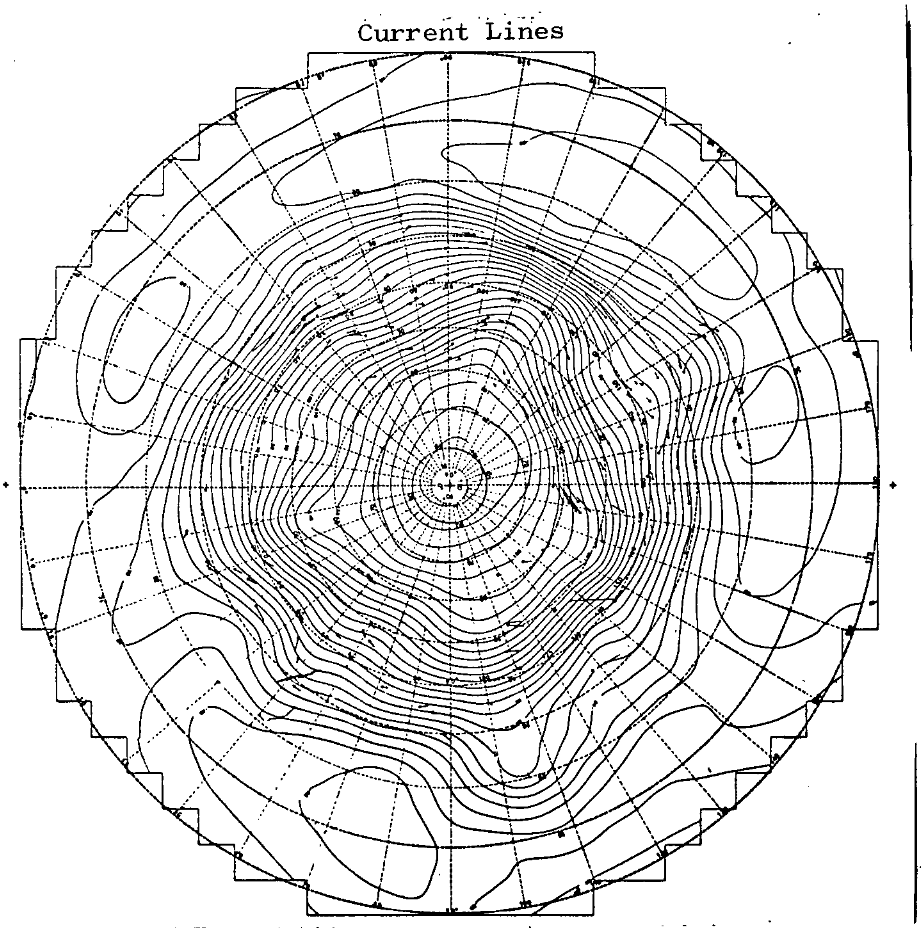

Figure 4. Map of atmospheric circulation in the southern hemisphere at the 200 mb level from balloon trajectories in the Eole experiment. Note that all small scale details have disappeared, the result of fairing the interpolations of the measurements.

One ordinarily is satisfied, in a like situation, to establish the mean, or statistical characteristics of a turbulent flow, the mean speed, the root-mean-square speed, and the like, for example.

That will not suffice here, however, because the object of weather forecasting is to determine the detailed, future evolution of each disturbance in atmospheric circulation from a known motion state. Here we have a problem comparable to that of forecasting ocean waves, knowing the precise shape, and the surface speed, of the sea at a given moment in time. It is pointless to dwell on the fact that here we have a very complicated mathematical problem, the result of the particularly great number of significant degrees of freedom that are present in fluid dynamics, a number so large that it is really impossible to consider all of them. This is why all forecasts of this type are erroneous within a very short period of time, within just a few days. A weather forecast thus can be useful only if it is constantly updated by constant, daily, observations of the global movement of the atmosphere. The forecast basically depends on the quality and the precision of the observation that fix the current weather situation.

Measure What or/and When?

Let us, for purposes of simplifying the problem somewhat, say that the circulation of the atmosphere at any given moment is determined by the two horizontal components of the wind, u and v. Evolution of the circulation, that is, the acceleration of the wind, is determined by the horizontal gradient of the pressure, p, at the altitude under consideration, z, in accordance with Newton's law, written here in Galilean coordinates

$$\rho \, du/dt + \partial p/\partial x = 0$$
$$\rho \, dv/dt + \partial p/\partial y = 0$$

Pressure p must be known at all locations, and at all altitudes. For this purpose it is sufficient to measure the total atmospheric pressure at ground level, p_s, and the vertical temperature profile, because an excellent approximation derives from the fact that the pressure and the altitude are linked by the hydrostatic equilibrium relationships, $dp = -\rho g dz$. A simple integration yields

$$p = p_s - \int_0^z \rho g dz$$

where the density of the air, ρ, can be calculated when the temperature is known. What remains is to find the variation in the atmospheric pressure, p_s, that is the result of the accumulation (or rarefaction) of the air in a vertical column, attributable to the convergence (or divergence) of the horizontal flow

$$dp_s/dt = -\int_0^{p_s} (\partial u/\partial x + \partial v/\partial y) \, dp$$

Finally, it would appear, as a result of this simplified analysis, that the essential dynamic parameters of atmospheric circulation are the pressure at ground level, wind speed, and air temperature at all altitudes. These are just the four major measurements made by the weather probes in the form of balloons, launched several times daily by each of the stations in the aerological observation network made up of the world's weather services. This remarkably efficient network makes it possible to collect all the observations from several hundred stations, /349 located primarily in the northern hemisphere, within two or three hours, and to analyze them at the World Meteorological Centers in Washington and Moscow.

Still, this network is inadequate, and for two reasons. First of all it contains enormous gaps, principally over the oceans and in the desert regions. Seventy-five percent of the tropics, and the Southern Hemisphere, are practically without conventional meteorological observations, those made by sounding balloons, and 25% of the Northern Hemisphere is without regular observations. Second, the spatial density of the soundings is marginal. Station spacing is of the order of 500 km, barely close enough together to detect disturbances with a wavelength of 1,000 km, those of the type where the experience (and the imagination) of the long-time analyst often is indispensable if very sporadic observations are to be interpreted and completed. We must, therefore, increase the number of observation stations in order to complete the Worldwide Meteorological Watch network, and obtain a really global determination of the state of the movement of the atmosphere at least once in 24 hours. Yet this is inconceivable because of the extremely high cost of the installations, and particularly of the weather ships assigned to fixed stations at sea. Significant improvement in our knowledge of the weather thus is economically impossible, impossible barring the use of new, less costly observation methods, automatic ones, necessarily. Because these observations must cover the globe, the best way to do so is to use a satellite in polar orbit that would circle all parts of the globe at 12 hour intervals. Another approach, one particularly suited to the tropics, is to set up a network of stationary weather observation satellites in the form of a belt in the equatorial plane. Equally possible, for this is essential, is local observance of essential atmospheric parameters by completely automatic stations set up in inaccessible regions, or at sea (on buoys), which would relay their data to weather centers via a satellite. All these methods will undoubtedly be employed concurrently in the next decade. In a word, then, all significant progress in our instantaneous knowledge of the meteorological situation is awaiting the implementation of these spatial observation methods.

This finally brings us to the problem of sharing these weather observations. Ideally, we should establish a complete map of all significant weather parameters at an initial given moment in time, and then, step by step, calculate the ultimate evolution of the general circulation. This is not possible on a practical basis because while the polar satellites record continuously, they see but a limited region of the globe at any given moment. Global coverage is available, but only in the form of a mosaic of regional maps complied for different times. The same is true of other facilities, particularly for the automatic buoy stations, or drifting balloons, which transmit haphazardly. The problem of collating all this information to provide a coherent representation of the general circulation at a given moment in time is not a simple one, but a solution is in sight, at least theoretically. One can conclude, therefore, that if one would be satisfied with observations, regardless of when made, it would be enough to make them within a reasonable time interval, 24 hours for example.

Televised Observation from Satellites

Tiros 1, the first weather satellite, was launched by NASA in 1960. Its television cameras provided the first pictures of the earth's cloud cover on a planetary scale. These pictures showed at once the quite characteristic forms in the cloud field, the most striking of which were the spiral shapes associated with hurricanes and tropical typhoons (Figure 5). Study of these shapes, and of their correspondence with definite meteorological phenomena, /350
proved to be so fruitful that the United States, soon followed by the USSR, had, by 1966, set up an operational system of photographic observation by satellites. This was the ESSA (1 to 9) series, a development of the Tiros in the United States, and the Meteor satellites put up by the USSR. These vehicles provide series of television pictures of the earth's surface, and of clouds, taken during the daytime and evidently using solar illumination. The pictures taken by a satellite in the course of the day, and assembled in convenient form, provide the means for reconstructing the whole of the cloud cover over the globe (Figure 6). In addition, a storage device provides for the temporary storage of each successive picture and for the quasi-instantaneous transmission of those pictures to all interested users within the range of visibility of the satellite with the necessary receiving equipment. This immediate, and automatic, picture transmission method, used with a space vehicle (Automatic Picture Transmission, or

the APT system), has opened up the era of instantaneous signaling of meteorological phenomena in a region encompassing several thousands of kilometers.

> An exact picture, taken every twelve hours, is sufficient to disclose and follow the progression of such large-scale disturbances as tropical cyclones.

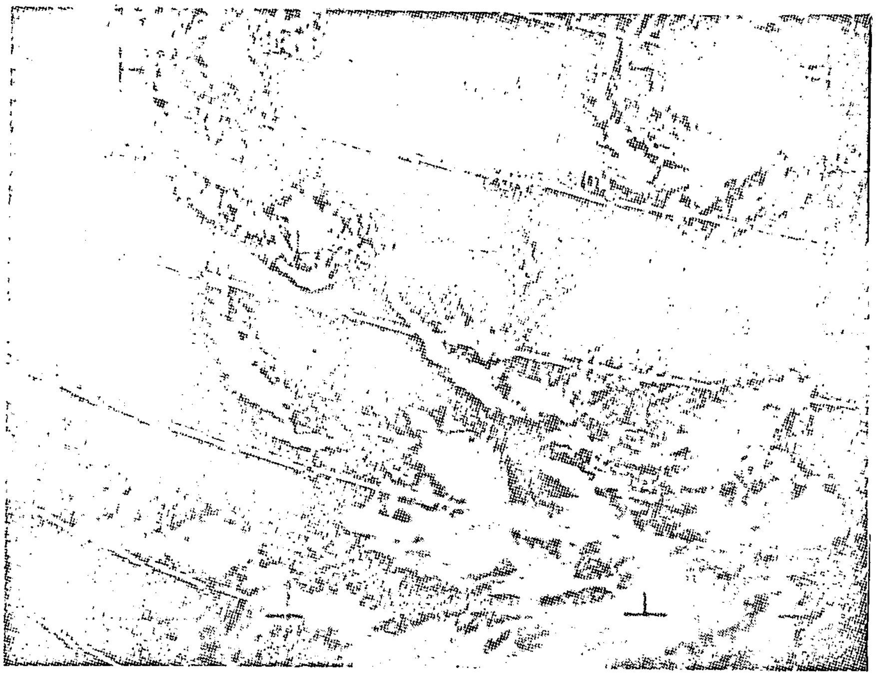

Figure 5. Photograph of hurrican Inez (5 October 1966) taken by a Tiros satellite over the Gulf of Mexico. The first pictures obtained by satellites showed at once the quite characteristic forms in the cloud field, the most striking of which, as can be seen in this photograph, is the spiral shape associated with hurricanes and tropical typhoons. Note the brilliant cirrus trails emanating from the intense convection cells over the South American continent and East Pacific Ocean, and blown by the violent winds. (NOAA photograph).

Establishment of fact is not forecasting, naturally, but the instantaneous signal does not detract from the invaluable services. First of all, a simple photographic extrapolation, based on approximate knowledge of large-scale atmospheric circulation, makes it possible to see such intense, locally constricted, phenomena as squall lines, or a discontinuity in the air masses, approaching. In fact, this extrapolation often is the only possible way to forecast very localized phenomena that will escape a radiosonde network a few hours in advance. On the other hand, instantaneous regional observation permits one to recognize certain relatively repetitive phenomena which experience tells one are probable. This is, in essence, a new, qualitative, even subjective, "meteorology," much like that used by old sailors, and completely foreign to the "mechanical" meteorology of Le Verrier and Richardson, but nevertheless effective and useful, when practised by masters of the art.

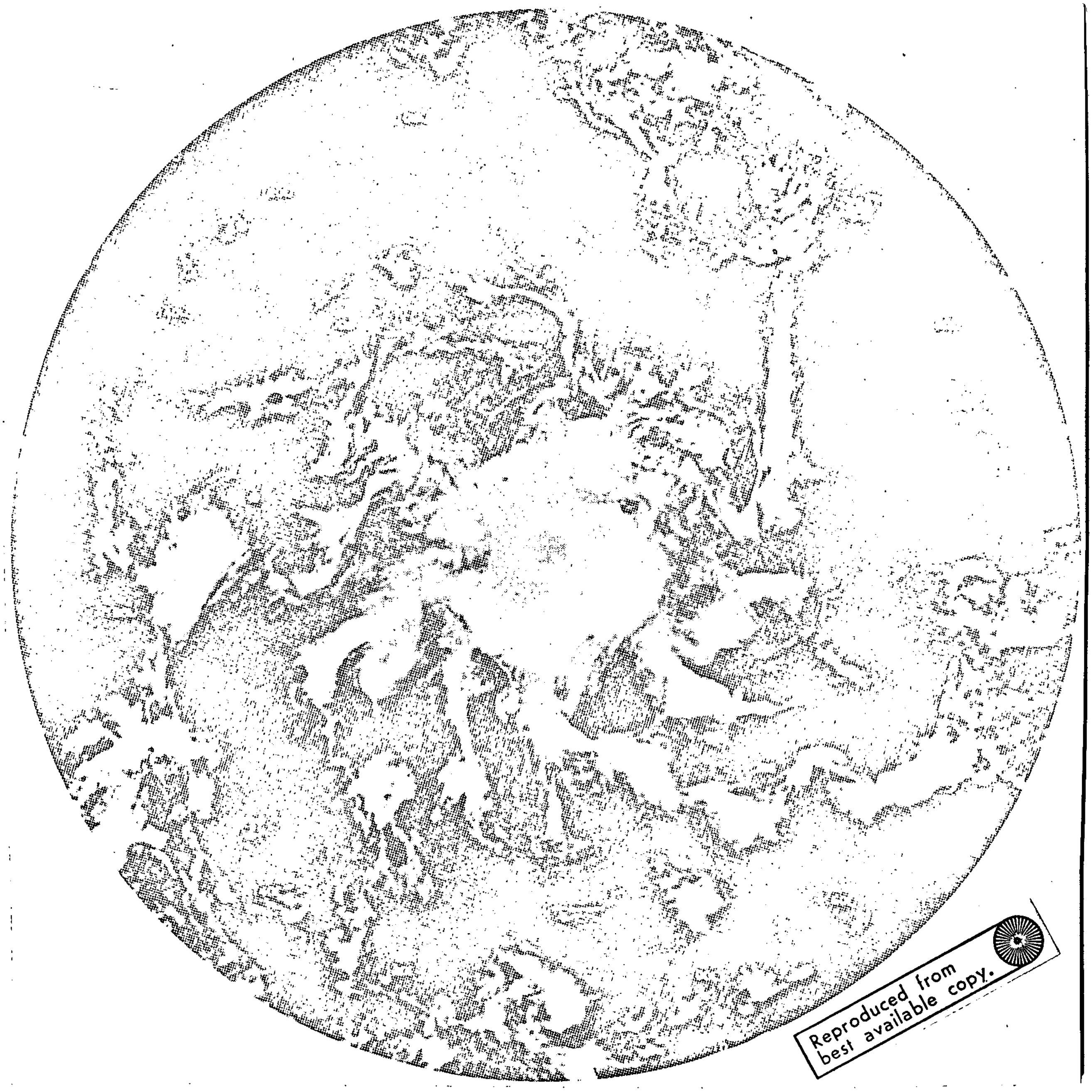

Figure 6. A mosaic of cloud photographs for a 24 hour period, taken by a Tiros satellite. This assembly, compiled with the aid of a computer, shows the Southern Hemisphere. Note the sharp outline of the Antarctic continent, covered with ice, and the cloud cover over South America. (NOAA photograph).

This subjective interpretation of APT photography soon (1973) will be aided by new refinements added to the ITOS (Improved Tiros Operational System) satellites. These will take pictures of the ground and of clouds day and night by using the thermal radiation from the objects themselves, the maximum of which evidently is in the far infrared (10-12 microns) because of their quite low temperatures. The sensitivity of the detectors, and the resolution of the image, are such that one will be able to detect objects, clouds, or terrain details smaller than a kilometer in diameter, and recognize the nature of the meteors observed with greater certainty.

The ITOS satellites have been placed in slightly retrograde circular orbits, that is, in orbits the axis of rotation of which make an angle slightly larger than 90° with the axis of the earth. This particular inclination (102°) was chosen so that the line of nodes advances a degree a day, that is, as much as the position of the earth around the sun. Given these conditions, the orbital plane always presents the same angle with respect to the sun-earth direction, and the satellite passes <u>at the same local (solar) hour</u> every day, a property that obviously is indispensable in order to provide for regular meteorological exploitation of the observations. In addition, this inclination of the orbit is close enough to 90° for the satellite to overfly all parts of the globe. Like the satellite in a strictly polar orbit, the ITOS satellites and the Russian Meteor satellites can observe the entire surface of the earth twice a day because of passage over a given area every twelve hours.

An exact picture every twelve hours is effective information, enabling one to discover and follow quite clearly the individual progression of the large disturbances. One can recognize at once the formation, and the development, of tropical hurricanes, and then track them day by day as they move toward the west and northwest. One also can observe the exact location of the large cyclonic depressions of the temperate latitudes that give birth to the severest of storms. Still, an interval of twelve hours is too long to discern the birth of smaller disturbances, those of great local importance. This interval still is too long, <u>a fortiori</u>, to track the movement of a mass of air marked by a particular group of clouds. Finally, one would like to see oneself in a very high observatory, constantly looking at the evolution of the tiniest of details, at the shape and the altitude of clouds. This dream too has come true through the space vehicles in a circular equatorial orbit at an altitude of approximately 36,000 km, and which provide us with the opportunity to look at the earth from a relatively fixed, or stationary, position above a given point on the equator. The stationary satellite thus is an ideal, fixed observatory for observing without interruption the meteorological phenomena that occur over a vast part of the terrestrial globe.

The Stationary Reconnaissance Satellites

Professor V. Suomi, of the University of Wisconsin, in 1966 convinced NASA technicians to include a small, 10 cm telescope, mounted on flexible bearings in the payload to be carried by the technological satellite, ATS-1. By combining the rotation of the satellite about its axis parallel to the axis of the poles of the earth with the progressive tilting of the telescope from north to south approximately every twenty minutes, he obtained a very detailed picture of the terrestrial disk, divided up into more than 2,000 successive lines (Figure 1). This system is the model for the scanning radiometers to be installed on board the future stationary reconnaissance satellites of the Worldwide Meteorological Watch.

Each picture shows the most recent meteorological situation, at worst with /352 but a few minutes delay, for a vast region in the form of a spherical segment covering one-fourth of the earth's surface. Enlargement of a part of the picture provides surveillance of a particular region, and detection of details scarcely more than 4 to 5 kilometer in size. Moreover, the continuous sequence of successive pictures comprises what is virtually a motion picture, much speeded up, obviously, of the development and displacement of cloud systems. One can detect a tropical convective cell and follow its growth, then its extinction. One can measure the increase in the cirrus cover at high altitude coming from this same cell, and can determine, in the flash of an eye, the organization of clouds into more or less structured and persistent systems, suggesting the presence of individual mechanical phenomena.

But above all, one gets the impression of movement very much like that one cannot help but attribute to atmospheric circulation as one compares the successive pictures one gets of the same cloud field, or, if one prefers, to the displacement of masses of air, marked by the presence of recognizable clouds. There are many cases of a cloud failing to move like the air surrounding it. This is what happens in the case of the "wave clouds" produced by the passage of humid air over a chain of mountains, for example. The same is true of the high cúmulus produced by intense convection and which traverse the major part of the troposphere like a chimney, without being trapped by the wind which blows around them. Despite these sources of confusion, and despite the great practical difficulties, such as matching views with respect to each other, identifying a group of clouds and following it from one picture to another, of determining the altitude at which these tracers are found, and others, the apparent displacement of the clouds from one picture to the next makes possible a quantitative measurement, from a distant satellite, of an essential dynamic parameter of the atmospheric circulation, that of wind speed. True, this determination is far from perfect. Absence of clouds, or, conversely, a too thick cloud cover, prevents the obtaining of measurements everywhere, or at several altitudes. Nevertheless, clouds are free, and their presence automatically provides the means for learning what the speed field of the atmosphere is over vast areas, particularly in the tropics, where no other observation (radiosonde) is available. The correlation of sequences of pictures of the terrestrial disk, taken from a stationary observatory, is, historically, the first method used to extract quantitative determinations from space observations of parameters that enter directly into the definition of the state of motion of the atmosphere and the numerical forecasting of its circulation.

Because of the extraordinary interest in these observations, the plans of the Worldwide Meteorological Watch, and of the Global Atmospheric Research Program (GARP), are based on putting up at least four stationary satellites, spaced as regularly as possible around the equator in order to provide complete coverage of the tropical belt and to observe the temperate regions up to 50 - 60° latitude (Figure 7). It is anticipated that one of these satellites will be European, the project known as the Météosat stationary satellite, developed by the Laboratoire de Météorologie Dynamique of the CNRS and the Centre National d'Etudes Spatiales.

The European Météosat Project

The Météosat is designed to provide day and night high-resolution pictures of the terrestrial disk, and of cloud masses, at a rate of one picture every 30 minutes. The difficulty of the undertaking can be summarized in two sentences. First, a detail of reasonable size, 4 km, for example, is seen from the position of a stationary satellite at a very small angle, approximately 10^{-4} /353 radian, or 20". Second, a complete picture of the disk contains a very great many resolution elements, of the order of 10 million. Hence, one must therefore make these 10 million measurements, but then must transmit them to the ground within 30 minutes. It is pointless to ask for more because the Météosat sensors, as well as similar devices built in the United States and Japan, are at the extreme limit of today's technology.

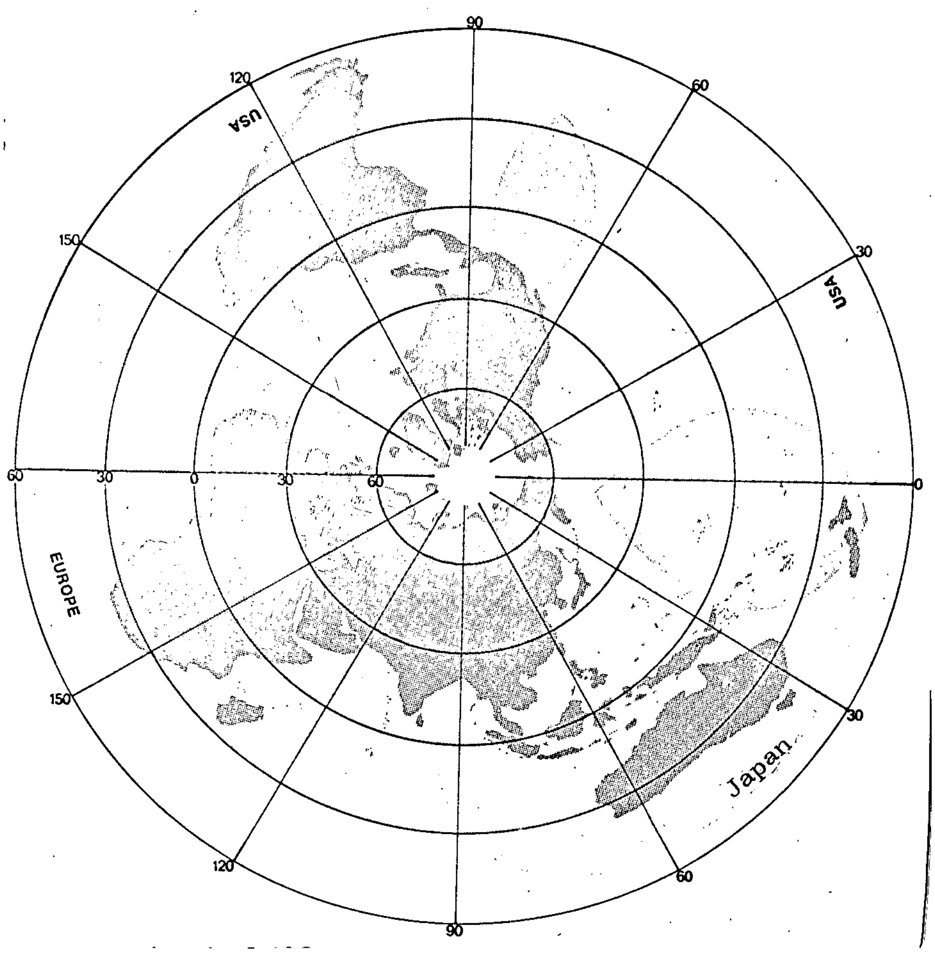

Figure 7. The positioning of four stationary satellites (two American, one Japanese, and one European), spaced as evenly as possible around the equator, is anticipated in the programs of the Worldwide Meteorological Watch and the Global Atmospheric Research Program. These satellites will make possible observations of the tropical belt and of the temperate regions to 50 - 60° latitude.

Because it has been desirable to follow the atmospheric circulation around the clock, it has been necessary to obtain photographs not only in visible light, but also to use the thermal radiation from the ground and from the clouds that emerge from the atmosphere in an "atmospheric window" between 10 and 12 microns. But these wavelengths already are in the far infrared and correspond to the low energy photons (0.1 eV) at the threshold of all the quantum photodetectors save one, the telluride-cadium-mercury semiconductor, HgTe-CdTe, the detection threshold of which can be reduced, at least in principle, to just about zero electron-volts by the proper dosage of the two constituents.

On the other hand, the radiation received from a distance of 36,000 km is very weak, so this radiation must be collected by a rather large telescope (400 mm) which must be firmly installed to resist the shocks and the vibrations of the rocket that takes it into space, and which then must be free to sweep the north-south direction, once in orbit, with a quasiastronomical precision of a few seconds of arc (Figure 8).

And the difficulties do not stop here. One must depend on the regularity of the rotation of the entire space vehicle in order to trace 2500 successive lines in a manner that will be reproducible while traversing the terrestrial disk. This means controlling the direction of the axis of rotation as well as the vehicle's internal transitory deformations in order to stay within a tolerance of about 10 seconds of arc, that is, much better than the tolerances for a good laboratory optical instrument! It also is essential that the satellite remain on station in its assigned position, despite small orbital error that may exist at the time it was positioned, and despite the disturbances caused by the sun's radiation pressure and the gravitational effects of the nonsphericality of the earth. One must thus be able to make necessary corrections to the trajectory by the use, for a calculated period, of small hydrazine rocket motors that comprise the satellite's propulsion system.

Finally, the information contained in the television pictures, about 200 million bits per picture, must be communicated to all users within the vast zone of visibility of the satellite. This means a constant information rate of 125,000 bits/sec, well beyond the capacity of the present ground communication lines (2,400 bits/sec for one special telephone line used to tie calculator to calculator). Ground communication lines capable of handling this information will

thus be prohibitively costly. The satellite itself must provide radio broadcasting of the data from high-powered transmitters operating in the decimeter band. The stationary observation satellite thus must link powerful sensors, much like those used for astronomical satellites, with the radio broadcasting equipment and the relays of a telecommunication satellite. This is why Météosat is not to be compared to Diamant, or Esro I and II, launched to date by CNES of the Organisation Spatiale Européenne. The vehicle will be about 2 meters high and about the same in diameter, weighing a little more than 250 kg, probably, and will only be capable of being launched by the improved American Thor-Delta rocket that will come into the arsenal in 1975. The communication system in the decimeter band will require the installation of new receiving equipment with 4 or 5 meter diameter parabolic reflectors, and of photographic recording equipment with resolution and fidelity not yet known. Nevertheless, the game is /354
worth the candle, for the result will be continuous and detailed surveillance of the meteorological situation over a zone equal to one-fourth of the surface of the globe.

Figure 8. The European Météosat stationary satellite is designed to provide high-resolution pictures of the terrestrial disk, and of cloud masses at a rate of one view every 30 minutes, day and night. This photograph shows the first mock-up of the radiometer for the Météosat satellite. The telescope ring is reflected in the primary parabolic mirror, 400 mm in diameter. (Photograph Engins Matra).

Météosat Characteristics

Orbit

circular, equatorial

altitude: 35,790 km

period: 24 hours

established geographic longitude: 10°E

Stabilization

gyroscopic, by rotation of the satellite as a unit at 100 rpm

pilotage (precession of the axis) by hydrazine rocket motors

Trajectory corrections

hydrazine rocket motors

Radiometer

channels: 1 infrared (IR): 10.5 to 12.5 microns
2 visible: 0.5 to 0.8 microns

picture coverage: 18° x 18°

resolution of television picture:
2500 lines x 2500 points (IR)
5000 lines x 5000 points (visible)

resolution on the ground: 4 km (IR)
2 km (visible)

picture interval: 30 minutes

main lens opening: 400 mm

Telemetering and relays

information rate: 125 Kbits/sec

frequency: 1700 MHz satellite/ground
2100 MHz ground/satellite

power: 1 main telemetry transmitter 1 watt
2 reradiation channels 10 watts

Geometric and mass characteristics

cylinder of revolution

height: 1.90 m

diameter: 1.90 m

mass (including hydrazine): 260 kg

From Nimbus to Itos

There can be no doubt that the brightest of the recent conquests of space observation methods is the one that makes it possible to measure remotely the vertical profile of the air temperature by analyzing the infrared radiation spectrum in the atmosphere. First performed using Nimbus 4 (1969), this technique provided surprisingly precise results right away (Figure 9). It should be noted that "spatial" sounding does not reproduce the detail of vertical stratification faithfully, particularly in the low strata, where the mean error is 2 to 3°C. Overall precision, however, is very good in the middle troposphere and excellent at high altitude (1°C).

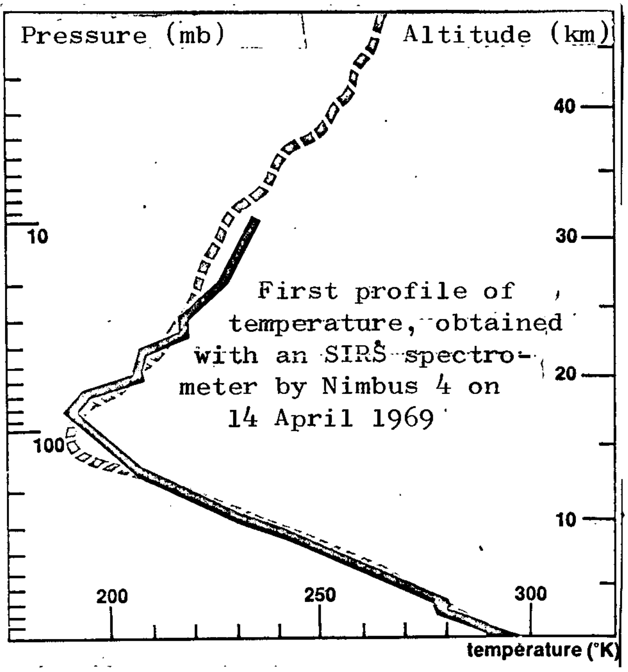

Figure 9. Measurement of vertical profile of the temperature of the atmosphere is an essential element of the success of the objectives of the Worldwide Meteorological Watch. This diagram shows the comparison between the profiles of air temperature measured directly by a radiosonde (solid curve) and indirectly by the SIRS infrared spectrometer on board Nimbus 4 (dashed curve). The measurement of the temperature profile by analysis of the infrared radiation spectrum yields remarkably precise results.

The principle is a simple one, involving the measurement of the spectrum, or, more precisely, several exact values of the monochromatic intensity of the infrared radiation leaving the atmosphere. This spectrum (Figure 10) shows a continuous background characteristic of the different absorbant molecules present in the atmosphere. The band used to reconstruct the temperature profile is that CO_2 gas, centered at 15 microns, because of the significant absorption, and the remarkably constant concentration of CO_2 molecules in the atmospheric mixture.

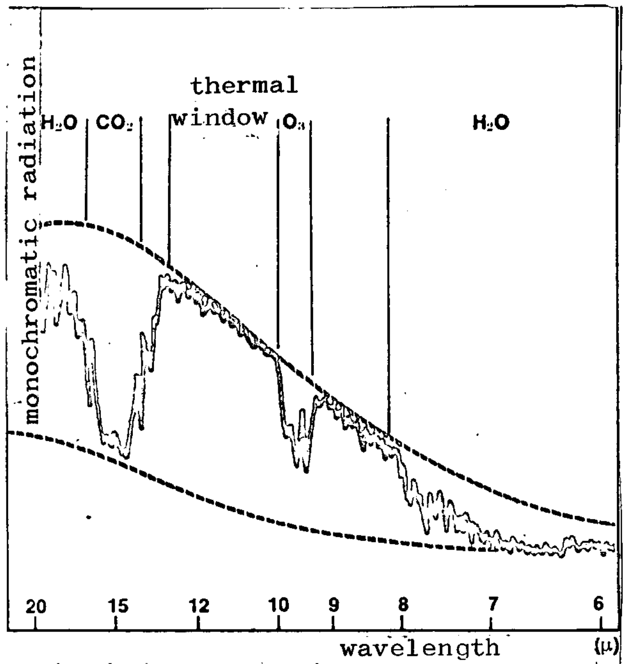

Figure 10. Spectrum of the infrared radiation emerging from the terrestrial atmosphere. Note the significance of the intense CO_2 absorption bands (15 microns), that of ozone (9.6 microns), and that of water vapor below 8 microns. The dashed curves represent the spectrum of thermal radiation from black bodies at 20°C and -60°C, respectively. Analysis of the spectrum yields air temperature profiles.

This selective absorption results in the atmosphere becoming what is essentially an opaque body at infrared radiation at 15 microns. The radiations emitted within it are reabsorbed almost at once, so that the radiation that finally does emerge does so at the "summit" of the atmosphere, or, if it can, in the upper tenth of the column of air (Figure 11). Note the characteristic shape of this curve, explained by the exponential rarefaction of the absorbant molecules near the high and near the low, by the equally exponential absorption of the radiation coming from the deeper strata.

On the other hand, it is obvious that the air is very transparent to radiation at wavelengths distant from the absorption bands such that the radiation received in the adjacent "atmospheric window" (10.5 to 12.5 microns) comes principally from the surface of the earth without great attenuation or contamination by the radiation from the column of air (a perfectly transparent object does not itself emit). Finally, at intermediate wavelengths the air is less

opaque than at the center of the absorption band, but less transparent than in /355
the window, and the radiation that does emerge comes from layers deeper and deeper in the atmosphere. A column of air traversed for a long time corresponds to a lower coefficient of absorption (Figure 11).

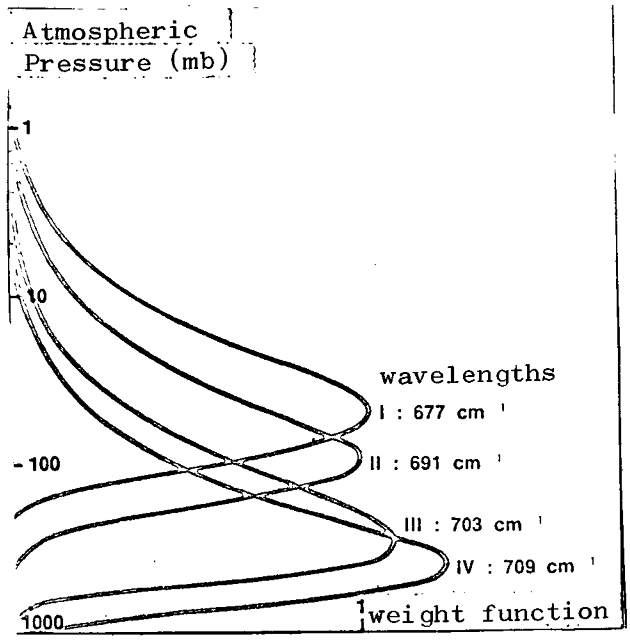

Figure 11. Relative efficiency of the different strata of the atmosphere as sources of radiation emerging near 15 microns (669 cm^{-1}). The radiation coming from regions higher (less dense) than the coefficient of absorption is greater.

Nevertheless, we know that the radiation (thermal) from an object is a rapidly increasing function of its temperature at all wavelengths. The monochromatic intensity of the radiation coming from the upper, cold layer of the atmosphere is much weaker than that of radiation coming from the low layers, or from the relatively warm ground. This easily serves to explain the shape of the spectrum observed; the absorption bands show as a marked depression in the spectral intensity of the radiation because the radiation is coming from colder regions. The contrary will be true of the temperature rises with altitude, as is observed effectively at the center of the absorption band corresponding to infrared radiation coming from the stratosphere that is warmer than the underlying layers.

Since it is possible to show in detail the shape of the spectrum of the radiation emerging if one knows the temperature at all altitudes (and the coefficient of absorption of the air, of course), we understand that it is equally possible to solve the reverse problem, that is, to deduce the vertical profile of the temperature, the monochromatic intensities at all wavelengths. In fact, however, the reverse problem has significant mathematical difficulties associated with it, and is not subject to strict solution in all its parts. But it has a practical solution, happily, provided adequately precise values of monochromatic radiations are available, something that is in fact the case when the normal absorption by CO_2 gas is not too greatly contaminated by such other opaque objects as clouds and fog. True, specialists still pale at the difficult problem of reconstructing what will be the radiation emerging from a column of clear air when one cannot measure the contaminated values attributable to the presence of the various aerosols. But the method that inverts the infrared spectrum already is exact enough for operational use in 1972 (the operational satellites Itos-D and following). Space observation thus will be able to furnish a one-time measurement of the temperature field for the global atmosphere once every 12 hours, made with a unique instrument carried over all regions of the planet in succession, with measurements made as if simultaneously by a great many individual, and different, sounding stations, and with a reasonable probability of success. Despite its drawbacks, particularly its sensitivity to cloud cover, radiometric measurements of the profile of the temperature is a long step toward a completely satisfactory realization of the objectives of the Worldwide Meteorological Watch.

Eole and the Automatic Stations /356

Many meteorological and oceanographic parameters still are inaccessible to remote observations based essentially on analysis of electromagnetic radiation received by a satellite. In the forefront of these is atmospheric pressure, which does not seem to lend itself to measurement by these indirect methods with the precision required for weather forecasting. This is why it is indispensible to measure these parameters directly, *in situ*, by appropriate sensors, such as thermometers and barometers, long since developed. But the land masses are vast, the seas even more so. The problem is not simply that of measurement, but rather that of communicating the results within a useful time span (a few hours). It is to this field then that space techniques bring an essential tool; the possibility of using transfer satellites to collect, while still fresh, the data from automatic measurement stations and store the information temporarily in their memory banks before retransmission to several central reception stations.

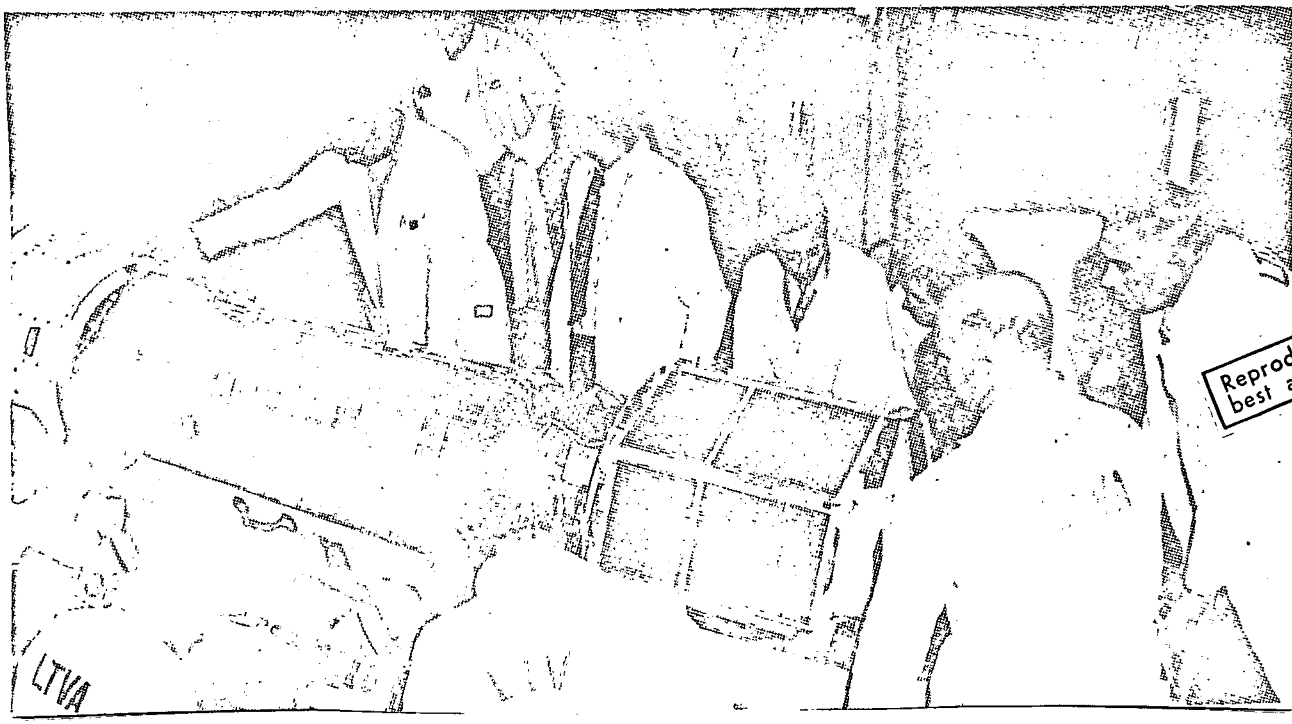

Figure 12. Installing the Eole satellite on the fourth stage (solid propellant) of a Scout rocket. To be seen underneath the satellite is part of the jettisonable fairing which will protect it during its passage through the atmosphere. Eole was developed by CNES for a meteorological experiment, the purpose of which was to determine the circulation of masses of air at an altitude of about 12,000 meters over the whole of the Southern Hemisphere at one time. It receives information from several hundred drifting stations carried by balloons. (Photo CNES-NASA).

The Eole satellite, developed by CNES and launched on a NASA Scout rocket (16 August 1971) is an example of just such a realization (Figure 12). This satellite was developed primarily for a meteorological experiment, the purpose of which was to determine the circulation of air masses at approximately 12,000 meters (the "jet stream") over the whole of the Southern Hemisphere at one time. The satellite is equipped to communicate with several hundred drifting stations /357 carried by inflated, inextensible balloons floating at a constant level in the atmosphere. It can thus receive navigation signals and a hundred bits of information in the form of short pulses (500 milliseconds) emitted by the balloons, located in an area over 2,000 km from the satellite. The same system has been in use since February 1972, to communicate with a group of 10 buoys drifting in the middle of the Pacific Ocean and measuring different atmospheric and oceanographic parameters. These buoys (Figure 13) can be the perfect prototype of future seagoing automatic observation stations measuring, as first priority, the pressure and temperature of the air, and the temperature of the surface layers of the ocean.

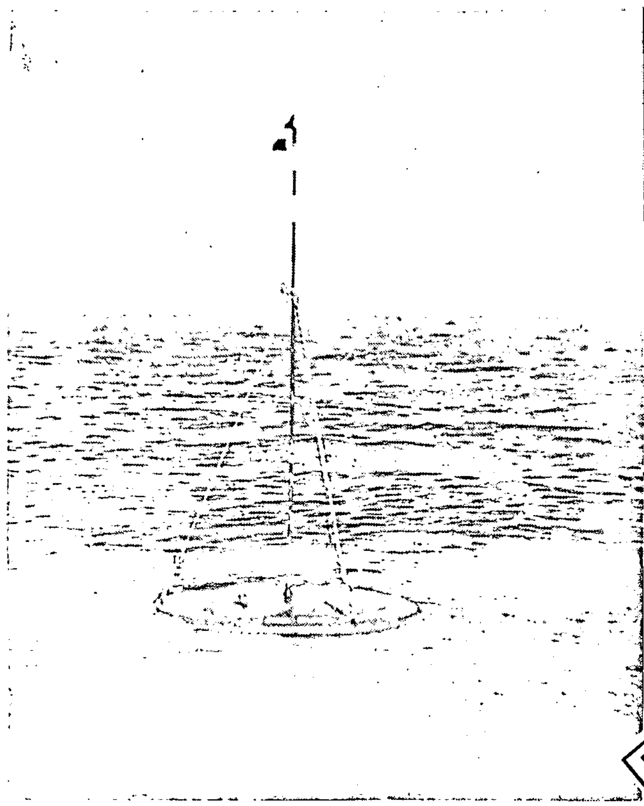

Figure 13. Drifting buoy equipped with meteorological and oceanographic instruments and a transponder for communicating data to the Eole satellite (Laboratoire de Météorologie Dynamique CNRS photograph).

France and the United States thus have decided to collaborate on the realization of an operational system for the collection of data that would be an integral part of the next generation of Itos meteorological satellites (1976, and beyond). This system will receive very short signals, emitted in a random rhythm by radioelectric beacons with just a few watts of power, and will record the coded messages contained in these short pulses at a rate of 400 bits/sec. One can hope that by 1976 we will have the equipment for the rapid collection of information scattered over the surface of the globe and transmitted by very robust radio beacons requiring little maintenance, or power. One also can think of the many meteorologists in isolated stations who will be able to type the results (codes) of their principal observations on a miniature keyboard connected to a buoy which will be responsible for automatically sending the message to the satellite.

Meteorology of Tomorrow

There is no doubt that this progress in instrumentation will bring about a vast improvement in meteorological information on a planetary scale when it is incorporated in the Worldwide Meteorological Watch program at the end of the decade. Simultaneously, the terrific progress made in the field of electronic computers provides us with the means for handling effectively this mass of information and for integrating the equations of the dynamics of the atmosphere in the global field with the sufficiently small horizontal links so that purely numerical errors will be negligible. All technical conditions thus will be joined to give the best possible dynamic forecast of the planetary atmospheric circulation. For what period can we hope to predict with certainty the evolution of this circulation? Probably for a little more than a week, but not much longer, for there is an intrinsic limit to the period during which a completely turbulent flow such as this can be predicted in a definite manner as a result of an initially known state.

It is obvious, as a matter of fact, that it is impossible to measure the briefest wind changes, and the most localized, every day, everywhere on earth. And even if they could be measured, there still would be the question of their explicit introduction into the numerical integration process. The calculation of the evolution of a model of the atmosphere of average sophistication (a cell 300 x 300 kilometers, 10 successive vertical levels) for one day of simulated weather would occupy a CDC 6600 computer for 2 hours. And the number of arithmetical operations is multiplied by 8 every time the dimension of the cells is divided by 2. The capacity of even the largest of the modern computers is reached very quickly (Figure 14).

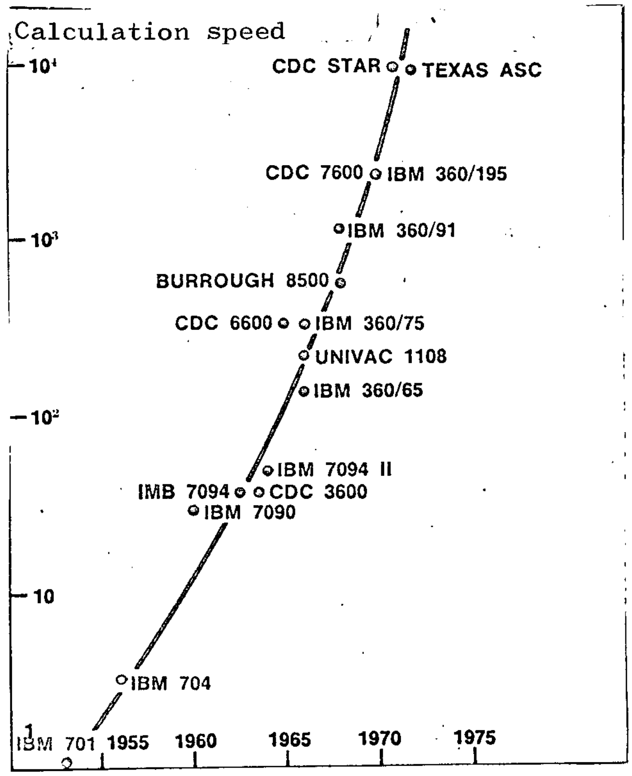

Figure 14. Progress in weather forecasting is intimately linked with the capabilities of the computers that process the data obtained by satellites. This diagram compares the performances of four generations of computers. The rate of execution of arithmetical calculations increases by a factor of 10 every four years.

As a result, the dynamic forecast of the flow is, of necessity, limited to just one part of the movements, and in order to know those the horizontal scale of which is greater than a certain limit, L, all small scale movements are purely and simply ignored, or treated in a purely statistical manner. These movements nevertheless exist in the real atmosphere, and they interact with /358 larger scale movements. Everything thus takes place as if we had taken for our calculation of the dynamic forecast a cut down description of the initial state of the atmospheric circulation, a description quite exact as of L, and totally false on this side of it. This error, initially confined to the region of small scale movements, those inferior to L, cannot help but infect the larger scale forecast. For we find that the time necessary for the error to increase from L to 2L is between 2 and 3 days, however great L. Since there are but three octaves approximately, between the scale of the disturbances one wishes to forecast (1000 - 2000 km), and the limit of resolution of our calculations (100 - 200 km), we can count on from 6 to 10 days of definite predictability. This, no doubt, is the result we can look forward to in the meteorology of tomorrow.

For most applications, however, it is not mandatory that the arrival of a cold front, or the outbreak of a shower be forecast within hours. It suffices to know the average characteristics of what the weather will be; more or less warm, more or less humid. There is no theoretical limit to this type of forecast, and it is possible that the very rapid progress being made in our knowledge of the physics of the atmosphere, supported by the results of a concerted world research program in this field (GARP) is conducive to a veritable <u>statistical forecast</u> with an average time of several weeks, nay, several months, in advance.

Finally, this accumulated scientific knowledge is the first step on the road to a detailed understanding of the processes that determine the climate of the planet, and one certainly can envisage the forecasting of the future evolution of this climate as a function of voluntary, or inadvertent modifications of this climate. This climate, which we consider so readily as something we can count on, is not, after all, as stable as we might think if we pause to consider that it has not been 20,000 years since the glacial caps covered the whole of Canada and the Scandanavian Peninsula, and that the level of the seas was 100 meters below today's level. It would be important, at the least, to know if the progressive cooling recorded over almost 5,000 years must carry us along toward a new glacial era, and if so when! But this is beyond the scope of meteorology of tomorrow, and will be the object of our scientific investigations for many years.

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